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SUMMARY OF FINAL REPORT FOR SERIES VII SOLAR ENERGY THERMIONIC CONVERTER DEVELOPMENT PROGRAM

February 1964

by

S. Merra

Prepared for

Jet Propulsion Laboratory
Pasadena, California

Approved by: Peter G. Pantazelos
P. G. Pantazelos
Director, SET Program

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SUMMARY

SERIES VII SOLAR ENERGY THERMIONIC CONVERTER DEVELOPMENT PROGRAM

I. INTRODUCTION

This document constitutes the final summary report of the work performed on the Series VII Solar Energy Thermionic Converter Development Program. The program was the part of the work of Thermo Electron's Contract No. 950228 with Jet Propulsion Laboratory covered by Work Statement No. 2739 and is a portion of JPL's contract NAS 7-100 with the National Aeronautics and Space Administration.

II. SERIES VII SET CONVERTER DESIGN AND COMPONENT TESTING

The general goal of the Series VII program was to develop an improved version of the SET VI converter to achieve increased life and reliability. An initial design decision was to leave unchanged the geometry of the generator cavity defined by the emitter pieces of Series VI converters, and to redesign the converter support structure so as to simplify generator assembly procedures.

The original design of a Series VII converter is shown in Figure 1. The major design changes incorporated from previous SET converters were a one-piece molybdenum collector, a seal structure utilizing pressed niobium flanges which eliminated the attachment of a separate emitter output lead ring, a lighter emitter (reduction of the mass by approximately 20%) to minimize the rate of creep, a cesium reservoir capable of achieving and maintaining optimum cesium vapor pressure during operation with minimum electrical power input, pinch-off formed by electron-bombardment melting rather than mechanical crimping, and a radiator capable of maintaining the optimum collector temperature during operation without an electrical heater.

Component development was pursued throughout the entire program with a major effort in the first two quarters and follow-on work during the rest of the program in an effort to thoroughly investigate the usefulness of each of these design changes. Improved methods were developed for machining and inspecting the thin tantalum sleeve, and measures were devised to minimize contamination of this component during outgassing. Tests were made to evaluate a new pinch-off procedure, which proved to be unsatisfactory, various braze joints, and cesium impurities. The results of these tests were incorporated into the design and assembly procedures established for the Series VII converters.

III. FABRICATION AND TESTING OF EXPERIMENTAL CONVERTERS

In parallel with the main effort of the SET program, a smaller supplementary task was pursued endeavoring to explore certain other promising converter concepts which, if successful, might be incorporated into the standard SET converter at a later date. Converters constructed in this task were designated with the prefix EX.

Prior to the work reported herein six such converters had been constructed. Of these, the first three were built to explore the use of rhenium emitters. Rhenium data taken by the Thermo Electron research department showed performance considerably better than that achieved with tantalum emitters. Converters EX-1, -2, and -3 were constructed in an attempt to reproduce this performance in SET type converters. However, to incorporate the rhenium emitters required the development of a method of brazing the rhenium to a tantalum substrate, and of the three converters only one, EX-1, reproduced the prior rhenium data. Another rhenium converter, EX-7, was constructed on this year's program to verify the EX-1 data. To the extent to which the conductivity of the heat path through the emitter structure can be determined, converters EX-1 and EX-7 compared well. Furthermore, the EX-7 data are comparable with data taken by Thermo Electron's research department on other rhenium converters.

Two additional experimental converters, EX-8 and -9, were also constructed this year to compare the performance of tantalum versus molybdenum collectors. Identical except for the collector surface material, EX-8 used a molybdenum collector and EX-9 used a tantalum collector. Figure 2 shows performance maps of the two converters at an emitter temperature of 1850° K. At this emitter temperature a marked difference in performance was observed between EX-8 and EX-9. At 0.75 volt output, for example, EX-8 has an output of 13 amperes compared with 6 for EX-9, thus suggesting that molybdenum may be a better collector material than tantalum.

In addition to constructing the three new EX converters, two others, EX-2 and EX-6, that were constructed and delivered on a prior year's contract, were returned to Thermo Electron for more extensive performance mapping. EX-6 used a tungsten emitter and tantalum collector. Earlier testing showed a performance well below both tantalum and rhenium converters, and the new tests confirmed the earlier results.

The additional testing of EX-2, on the other hand, resulted in very significant new information. The performance of EX-2, when carefully mapped and compared with EX-1, showed a very similar difference in performance to that between converters EX-8 and EX-9. Since EX-1 and EX-2 differ principally in that the former has a molybdenum collector and the latter's collector is tantalum, further support is given to the significance of the differences in performance of EX-8 and EX-9. These data indicate clearly that the use of a molybdenum rather than tantalum collector in SET converters should be pursued further.

IV. PROTOTYPE SERIES VII CONVERTER DEVELOPMENT

During the first three quarters, seven Series VII prototypes were built and tested. These converters are designated VII-P-1 through VII-P-7. The major problem encountered during the development of the prototypes was degradation of the power output with time. In all cases a black collector deposit was observed in those converters which deteriorated. In addition to presenting an electrical resistance between the emitter and collector surfaces, this deposit increases the collector work function. Collector work function measurements were made on SET VII-P-3 and SET VI-S-11, and these were compared. The results (Figure 3) of the work function determination demonstrated an increase of the collector work function by approximately 0.23 volt for VII-P-3 over SET VI-S-11, which had no record of degradation.

Through the use of a number of analytical techniques, it was determined that the deposit could have resulted from the reaction

$$2\text{-}1/2\ SiO_2 + 2\ Ta \underset{2000°K}{\overset{1000°K}{\rightleftarrows}} 2\text{-}1/2\ Si + Ta_2O_5.$$

As a result of this explanation, steps were taken in the design, construction and outgassing of diodes VII-S-4 and -5 to further reduce reactions between the glass containers and the bulk cesium. Glass is one of the most obvious sources of silicon contamination in converters. This was accomplished by incorporating a cesium reservoir and tubulation assembly which from experiments were known to maintain the glass cesium capsule envelope below 250°C at all times during the processing of the converter.

The prototype development results were used to redesign and fabricate two additional converters, SET VII-S-4 and -5, which were then acceptance-tested and mounted for life testing.

V. FABRICATION AND ACCEPTANCE TESTING OF SERIES VII SET CONVERTERS

During the last quarter of the program, seven carefully constructed Series VII diodes were built and tested. The design was identical to VII-S-4 and VII-S-5 which were life-tested. Figure 4 shows an over-all view of a SET VII converter which has been fabricated, outgassed, and acceptance-tested. Figure 5 is a close-up of the emitter and sleeve of the same converter. The exceptionally clean appearance of the tantalum may be noted. Figure 6 shows seven SET VII diodes which were fabricated, while Figure 7 shows the SET VII diode and an exploded view of the various components of the converter in a typical assembly area (dust-free hood). Figure 8 shows a close-up of the various diode components. During fabrication, no complications were encountered in brazing the various components. During the fabrication and outgassing, special care was taken to carefully follow the product specifications and to apply the quality-control inspections adopted during the prototype development. The cleanliness achieved as a result of this outgassing is clearly demonstrated by Figures 4 and 5.

The results of the acceptance tests are listed in Table 1. As can be seen from these data, the performance of the diodes varied. The differences in power densities at one volt between the highest and the lowest performance diodes is

2.7 watts/cm^2. Only limited test data are available on these diodes because the program called only for measuring the output power at an output voltage of one volt and an observed emitter temperature of 1700° C with the cesium temperature optimized. Also, no means were available for varying the collector temperature.

The wide variation in these test results between various diodes was very surprising, in view of the extremely careful control that was exercised during the construction and processing of the diodes. Consequently, a careful analysis of the test results of the diode design and construction was made to try to determine the cause of the variation. This analysis indicates that the probable cause was variation in collector surface temperature, which was not optimized during testing because a heater and cooling arrangement is not included with the diodes.

To verify that the collector surface temperature was the cause of the variations in performance, diode VII-S-7 was again placed on test with a cooling strap added to the radiator to reduce the temperature. When the collector temperature was lowered by 50° C, the performance of the diode increased to 8.7 watts/cm^2, making it very close in performance to the best of these Series VII diodes. This result clearly indicates the desirability of much more extensive testing of the Series VII diodes than was permitted under the approved scope of the program.

VI. LIFE AND RELIABILITY TESTING

During the program, three Series VI and two Series VII converters were placed on life test. The objective of the life tests was to demonstrate that a life of 2000 hours at 2000°K emitter temperature could be achieved in a hardware-type solar thermionic converter without significant deterioration of output with time. From earlier system considerations, the SET VI diodes were acceptance- and life-tested at 1 volt at 1655°C observed emitter temperature, while more recent considerations led to testing the SET VII diodes at 0.8 volt. Neither voltage represents either the maximum power or efficiency point. The acceptance test data is summarized in Table 2. Each converter was placed in a life test chamber (shown in Figure 9) and was set initially at a value as close as possible to the initial conditions. The initial starting points for life testing are shown in Table 3. When steady-state conditions had been achieved, each converter was then maintained at constant heat input to simulate solar heating.

During previous life tests on Series V diodes, reactions had occurred between the hot diode emitter structure and oil vapors from diffusion-type vacuum pumps. Also, localized bombardment of emitters by the filaments of electron-bombardment heaters was observed, resulting in excessive localized crystal growth. Considerable time and effort was expended on this program in the design and fabrication of five new life-test units to ensure that the vacuum environment, the method of heating, and the method of testing would not jeopardize the life of a diode. These units, pictured in Figure 10, eliminated virtually all of the problems encountered in previous long-term converter testing and performed very well throughout the life tests.

Figures 11 through 15 show plots of power input, power output, and observed emitter temperature versus time. For converter VI-S-18, which accumulated a life of 3342 hours without failure, the average order of change between initial and final operating conditions was 10%, while for VII-S-4, over 3212 hours without failure, it was less than 2%, for VII-S-5, over 3185 hours without failure, it was 12%, for VI-S-14, over 3013 hours without failure, it was less than 25%, and for VI-TEP-1, 3010 hours without failure, it was of the order of 40%. VI-TEP-1 also had a recorded emitter temperature 20°C lower than its initial value for the last 2000 hours of testing, suggesting a change in heat input to the converter.

Figures 16 through 20 show views of each converter before and after life-testing. These photographs show no perceptible changes in the diode components after 3000 hours and suggest that the maximum life capability of the Series VII SET converter may exceed 3000 hours by a substantial margin.

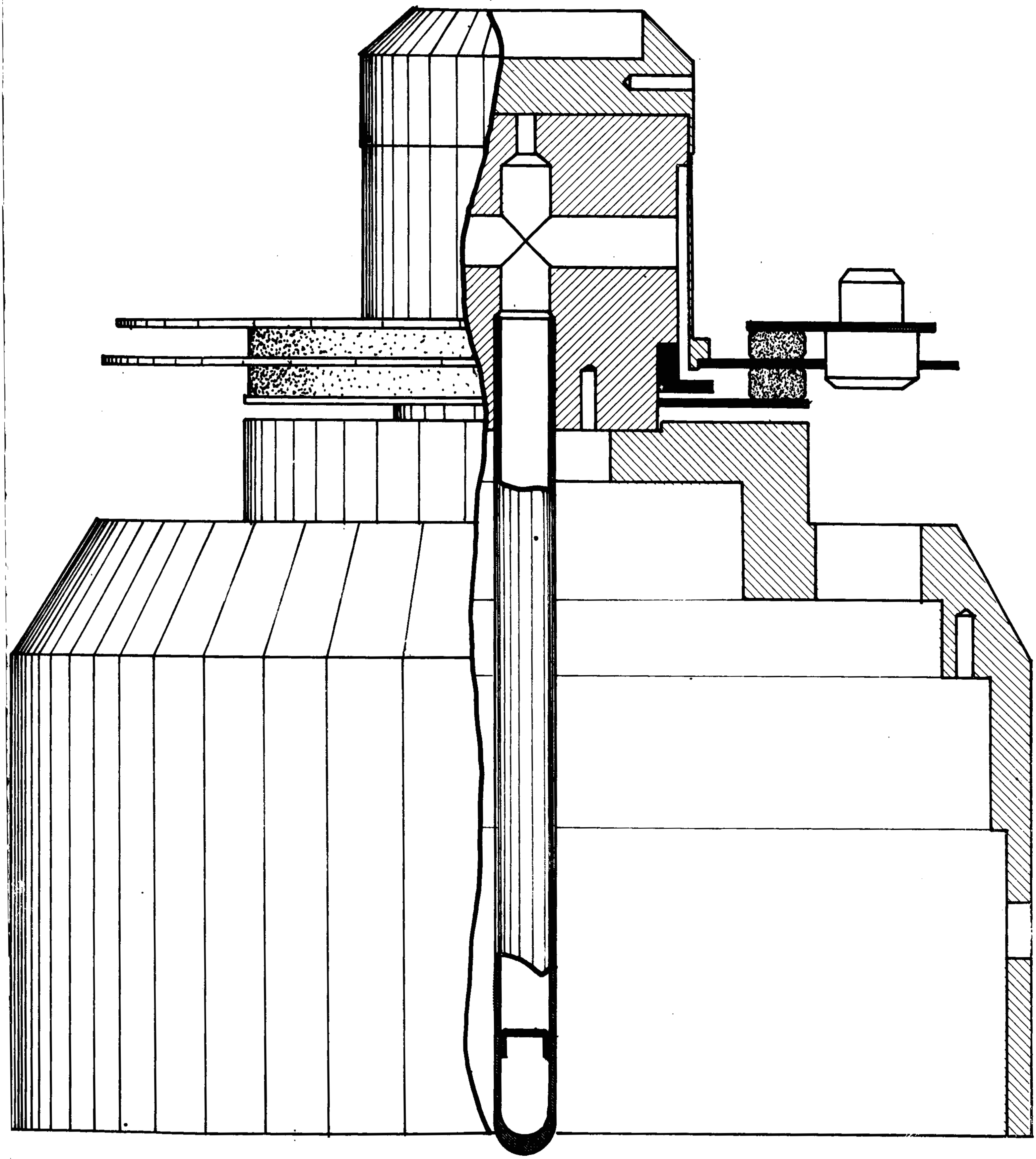

Figure 1. Preliminary Design of Series VII Converter

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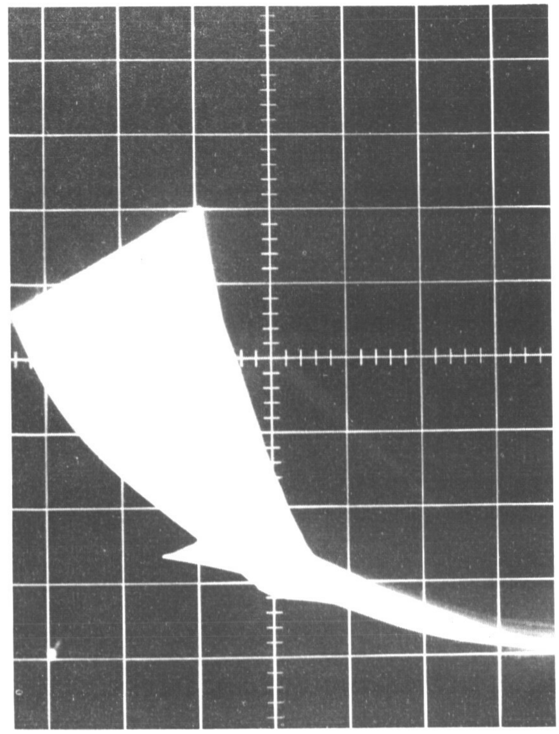
Figure 2(a). EX-8 at $T_E = 1850^oK$

T_E = 1850°K

$T_{(Coll)}$ = 845°K

T_{Cs} = 580-647°K



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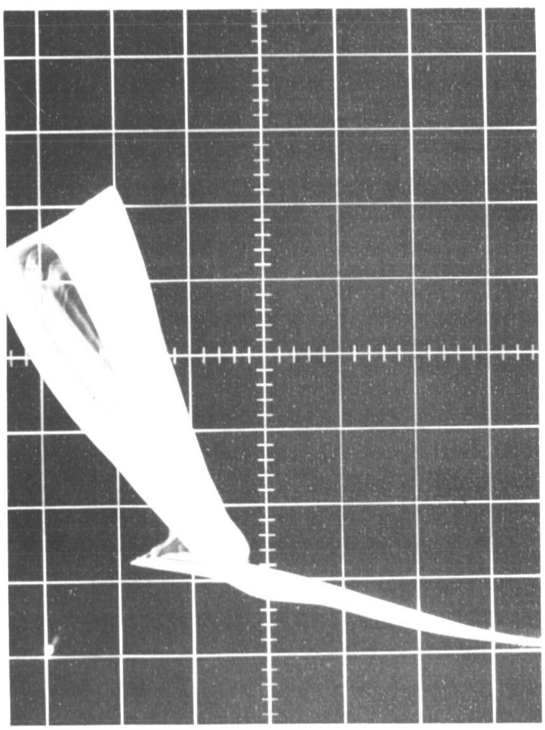

Figure 2(b). EX-9 at $T_E = 1850^oK$

T_E = 1850°K

$T_{(Coll)}$ = 865°K

T_{Cs} = 592-652°K

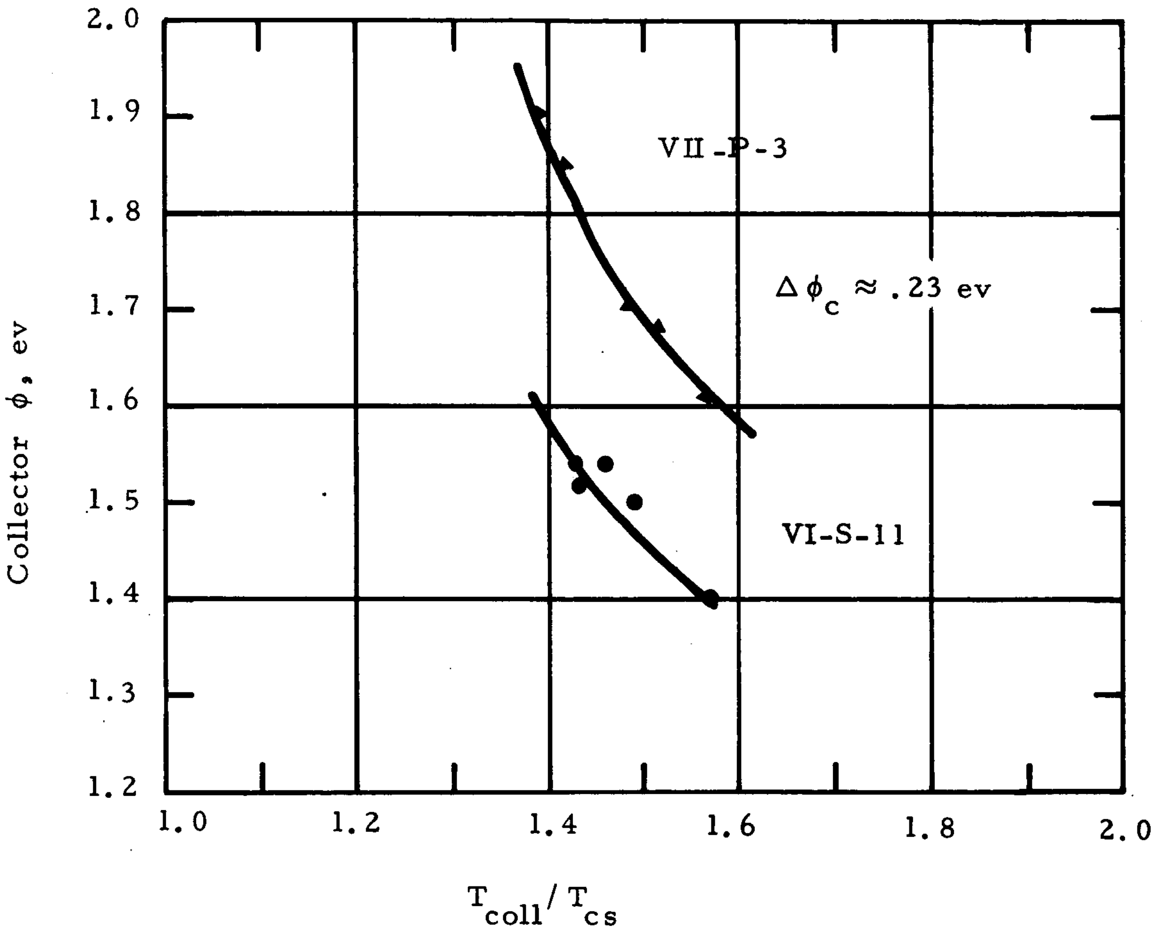

Figure 3. Results of Ten Diagnostic Experimental Runs for Collector Work Function Determination

Figure 4. SET VII Diode

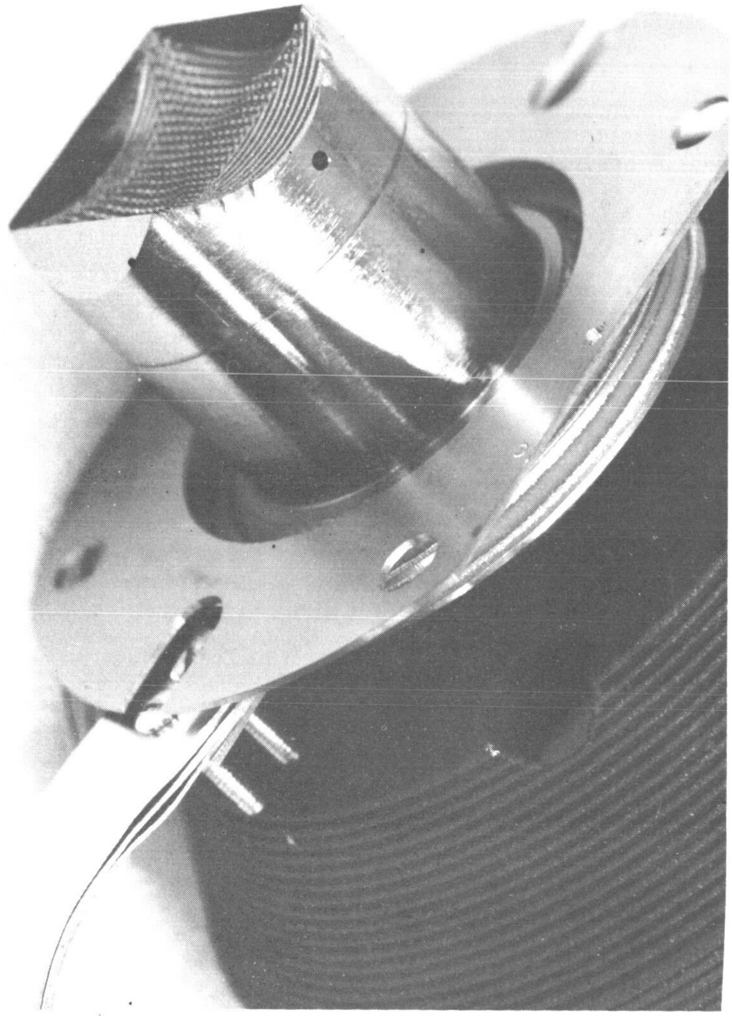

Figure 5. SET VII Spacer

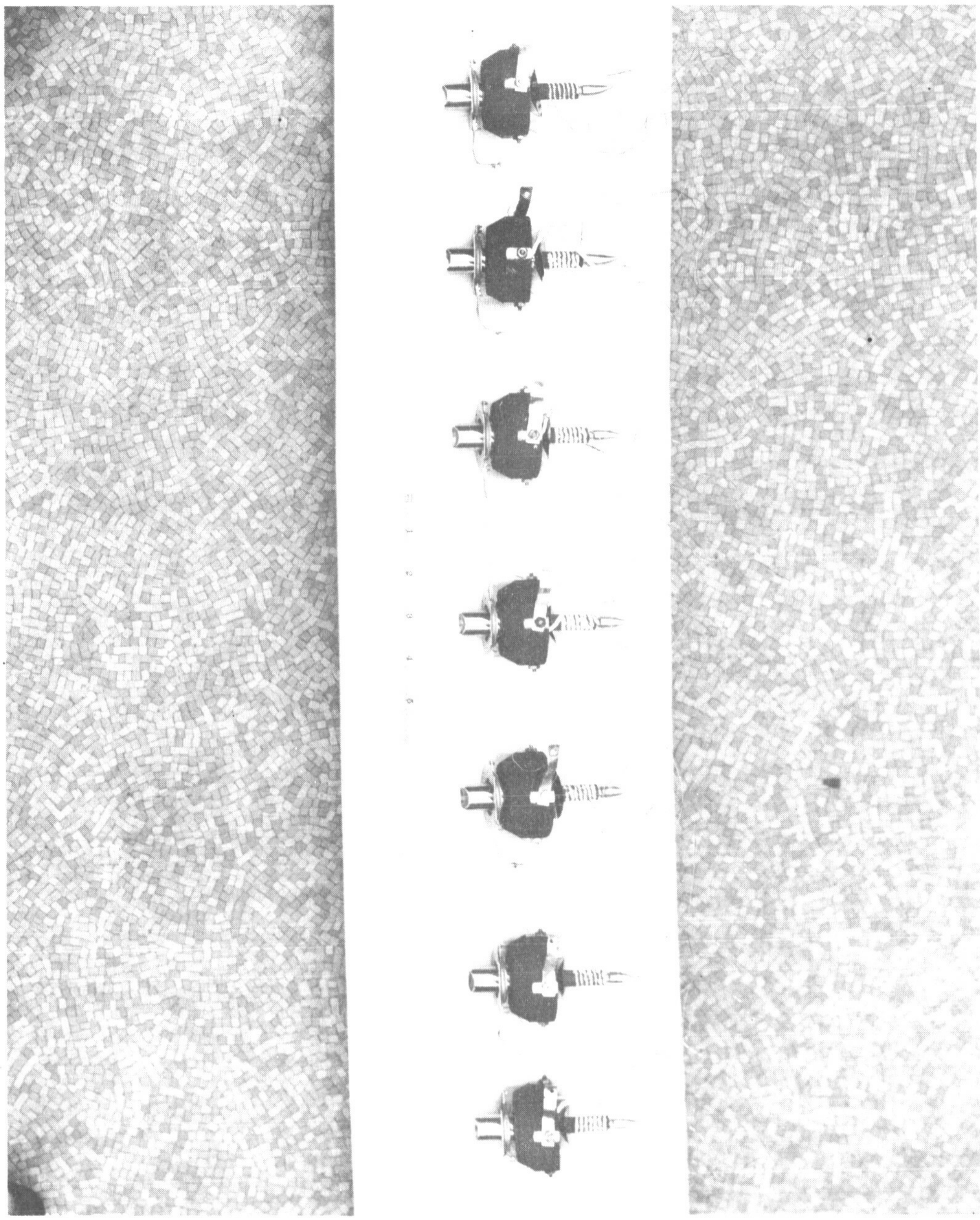

Figure 6. Seven SET VII Diodes

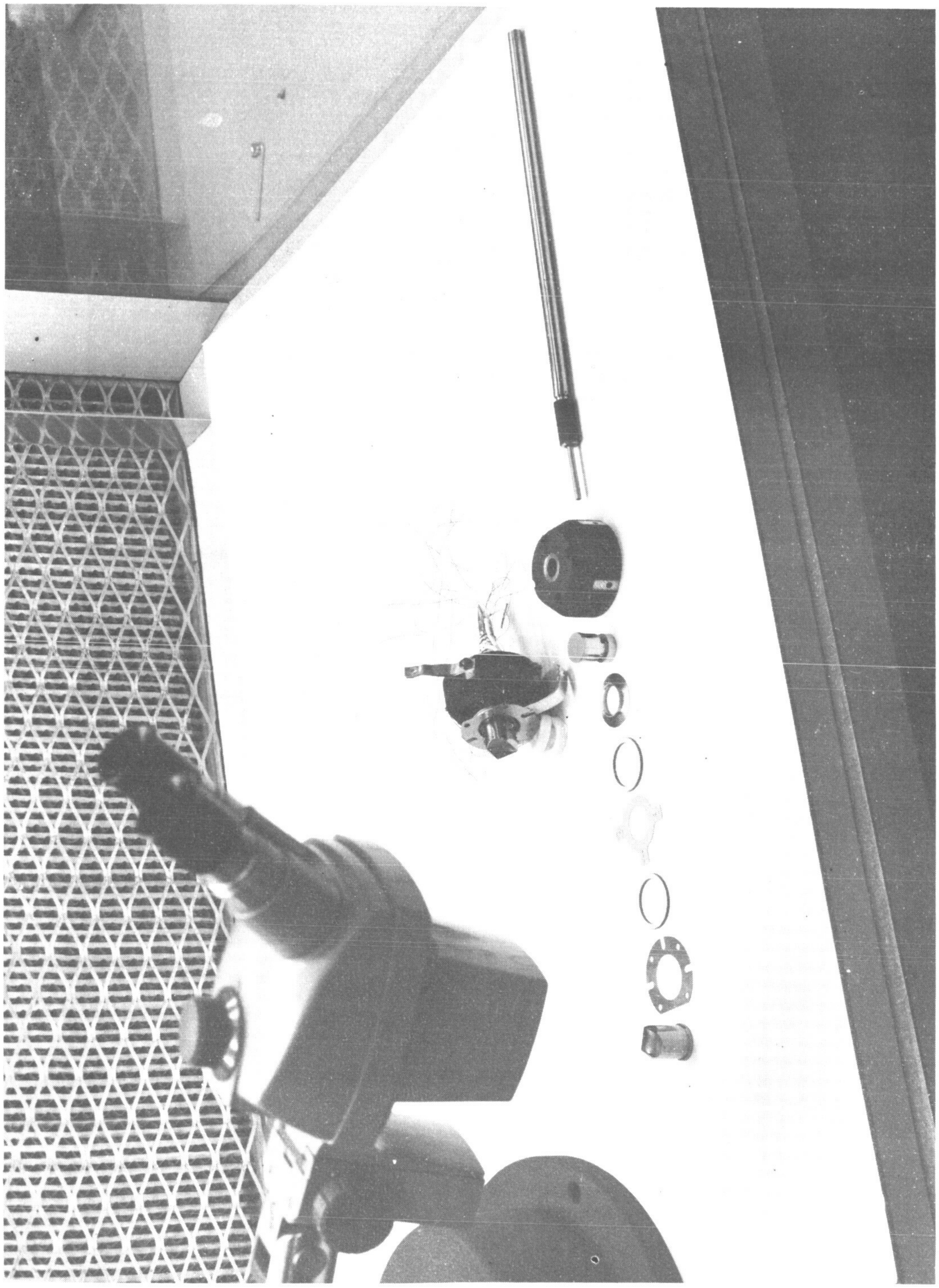

Figure 7. Dust Free Hood, Microscope, Exploded View SET VII Parts and SET VII Diode

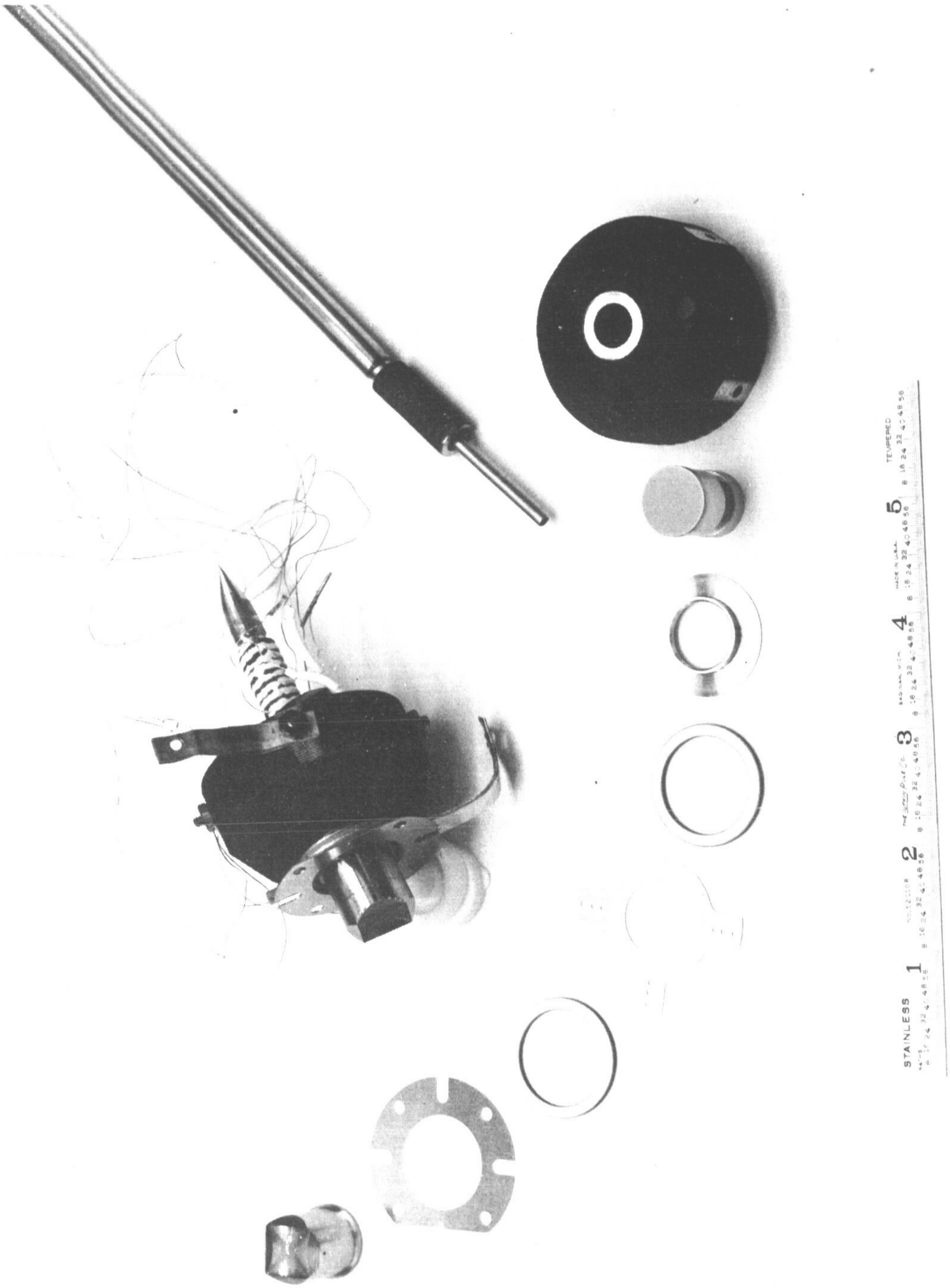

Figure 8. Exploded View of SET VII Parts and SET VII Diode

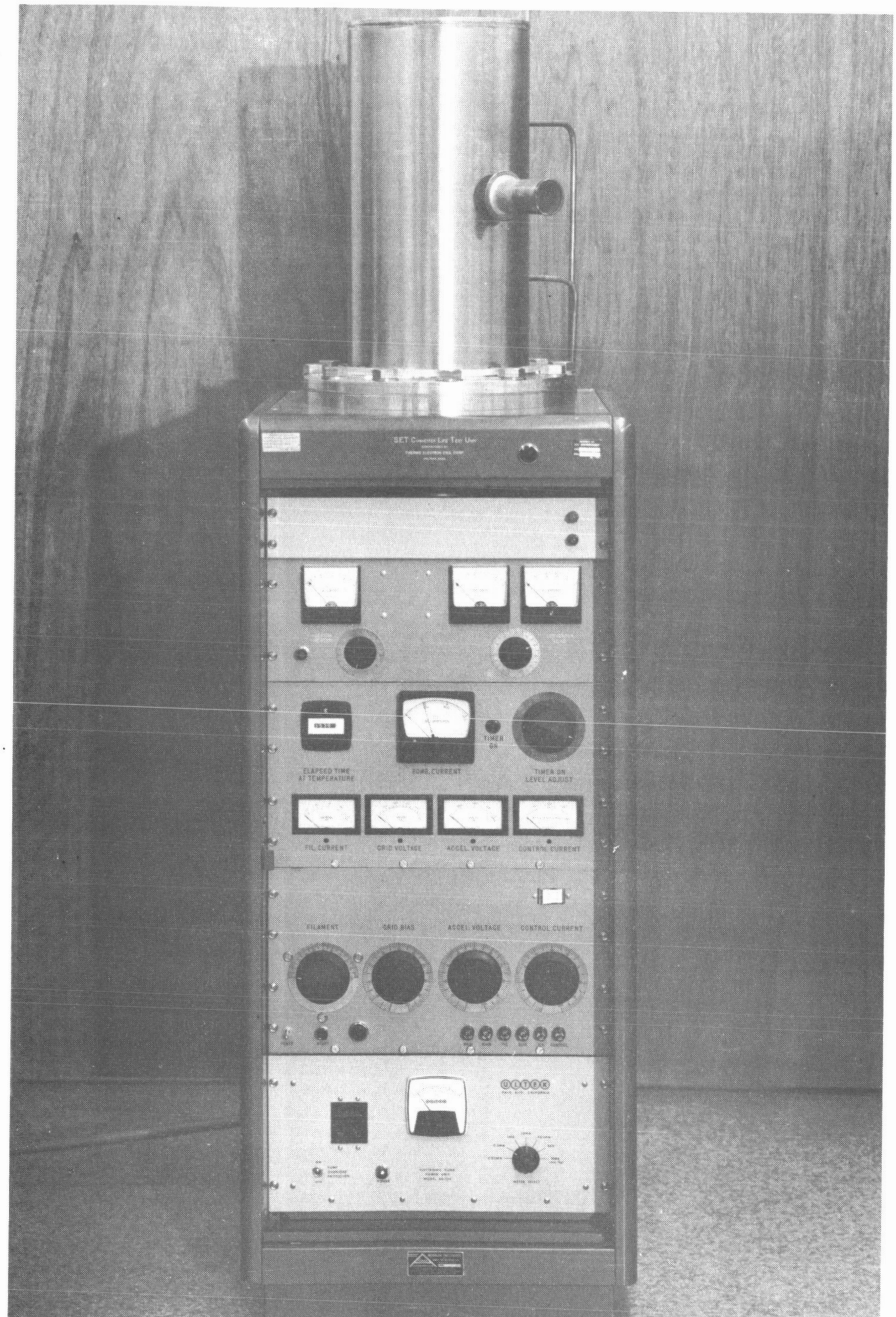

Figure 9. Instrument Panel and Chamber of a Complete Life Test Unit

Figure 10. Five Life Test Units

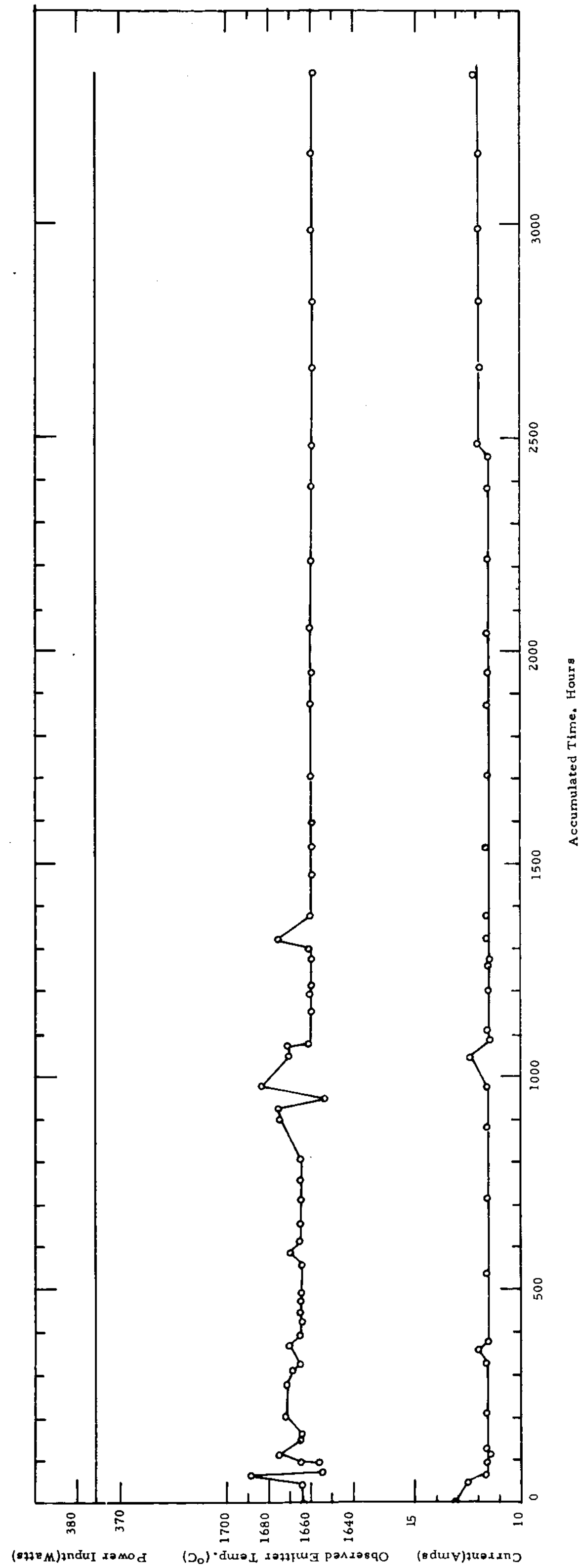

Figure 11. Converter VI-S-18, Power Input, Power Output, and Observed Emitter Temperature Vs. Time

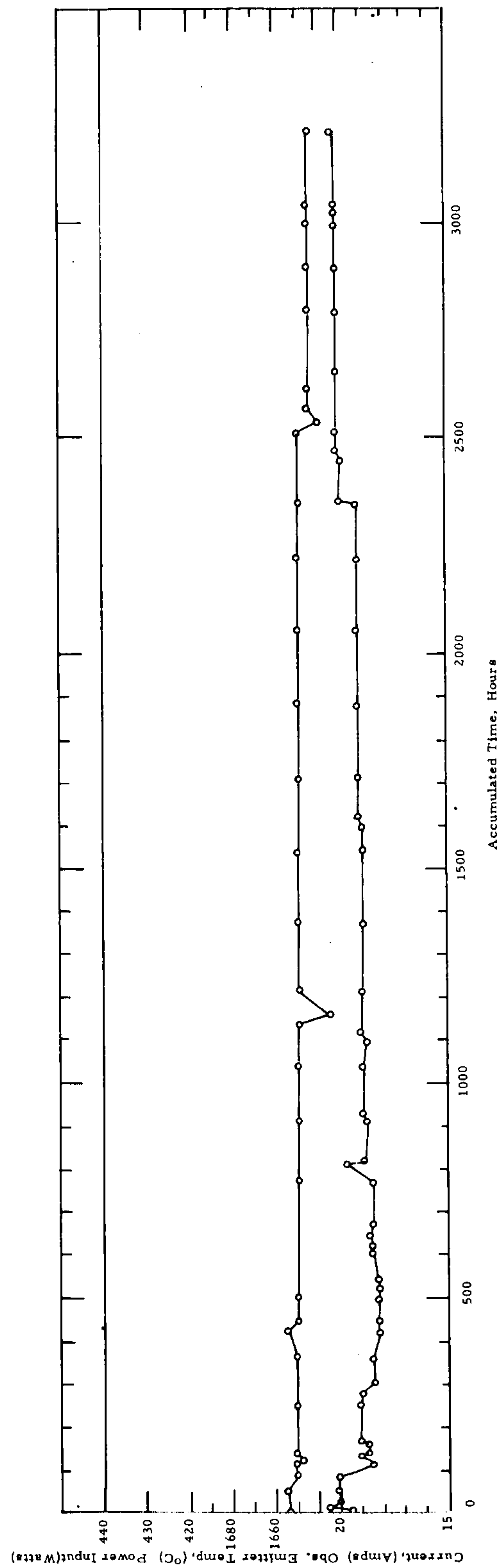

Figure 12. Converter VII-S-4, Power Input, Power Output, and Observed Emitter Temperature Vs. Time

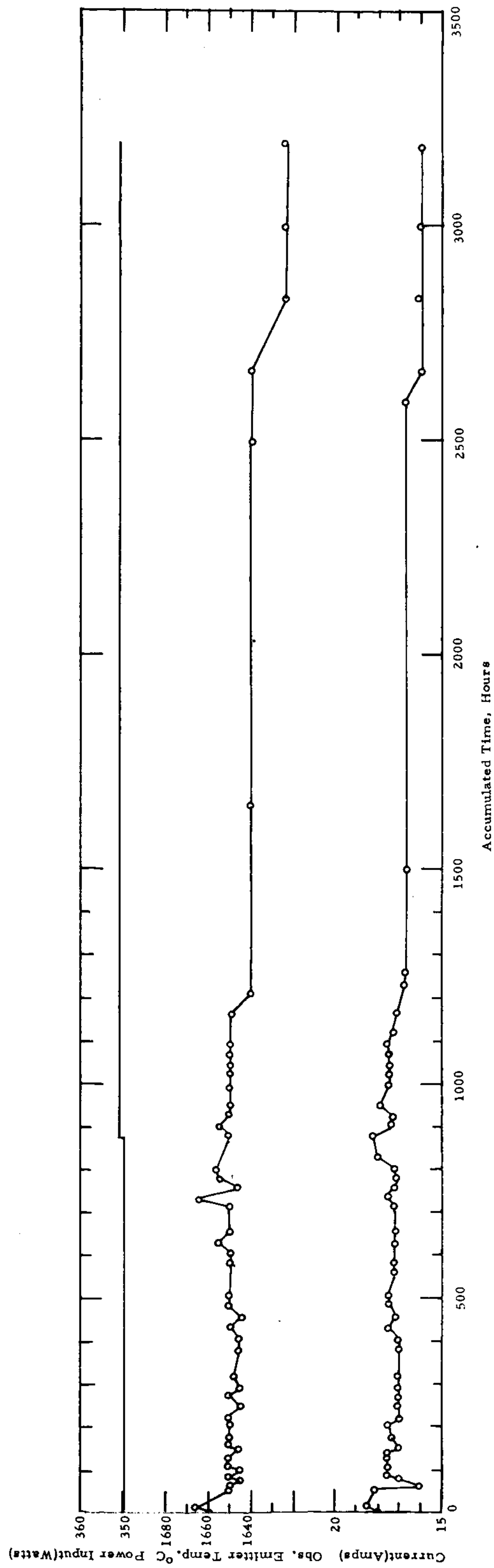

Figure 13. Converter VII-S-5, Power Input, Power Output, and Observed Emitter Temperature Vs. Time

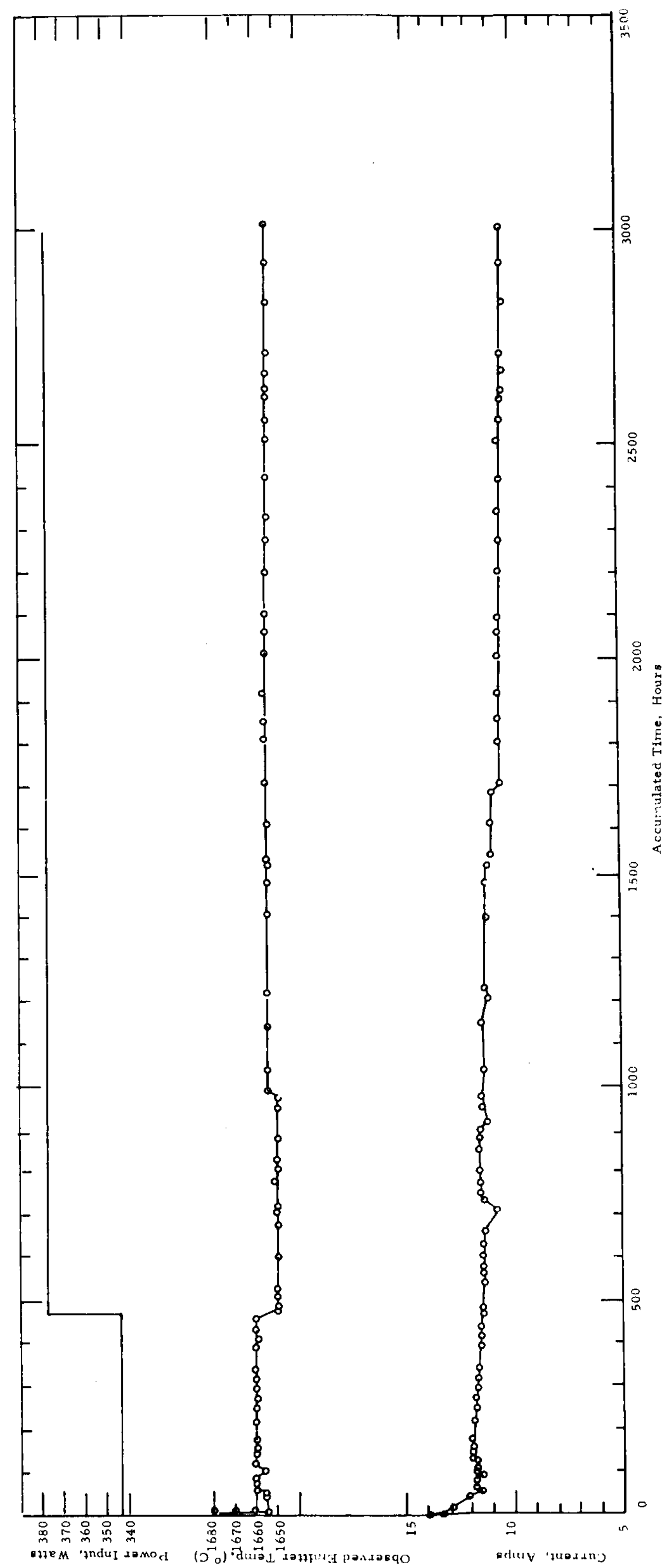

Figure 14. Converter VI-S-14, Power Input, Power Output, and Observed Emitter Temperature Vs. Time

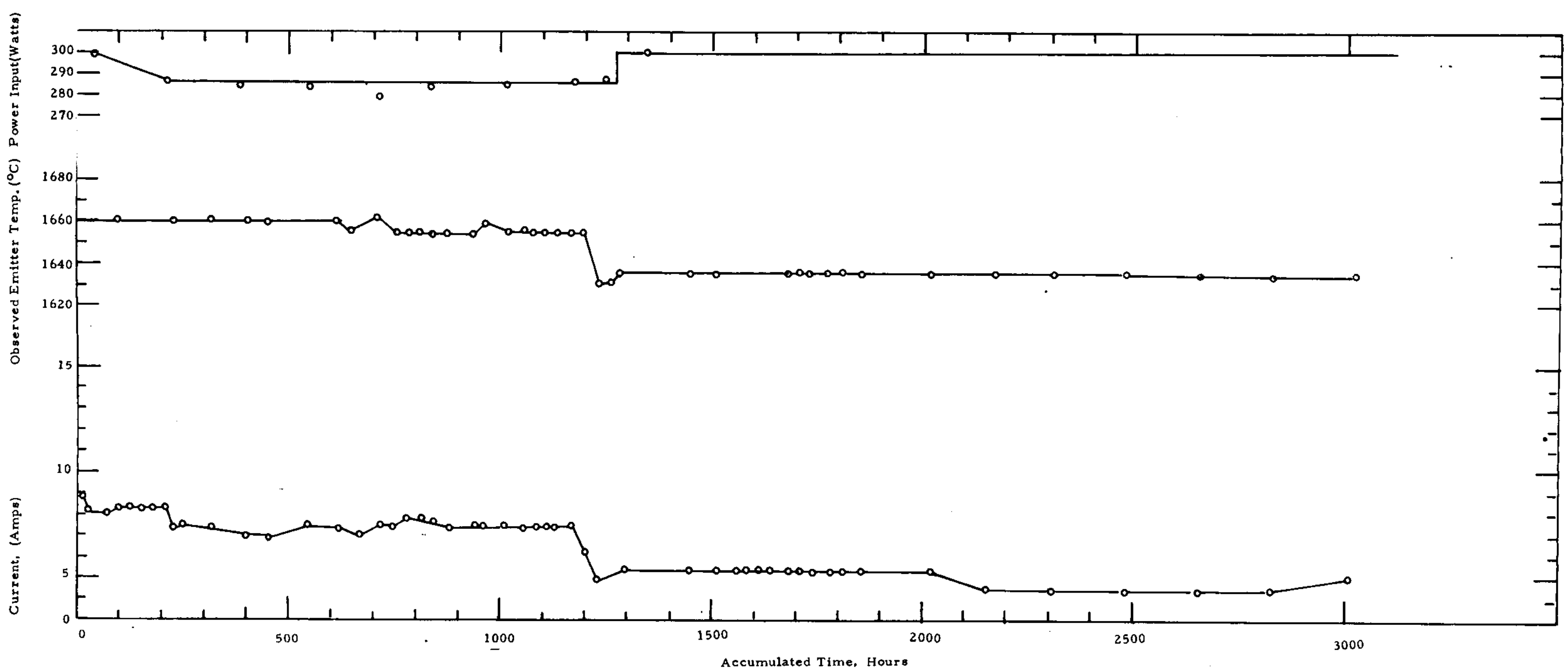

Figure 15. Converter VI-TEP-1, Power Input, Power Output, and Observed Emitter Temperature Vs. Time

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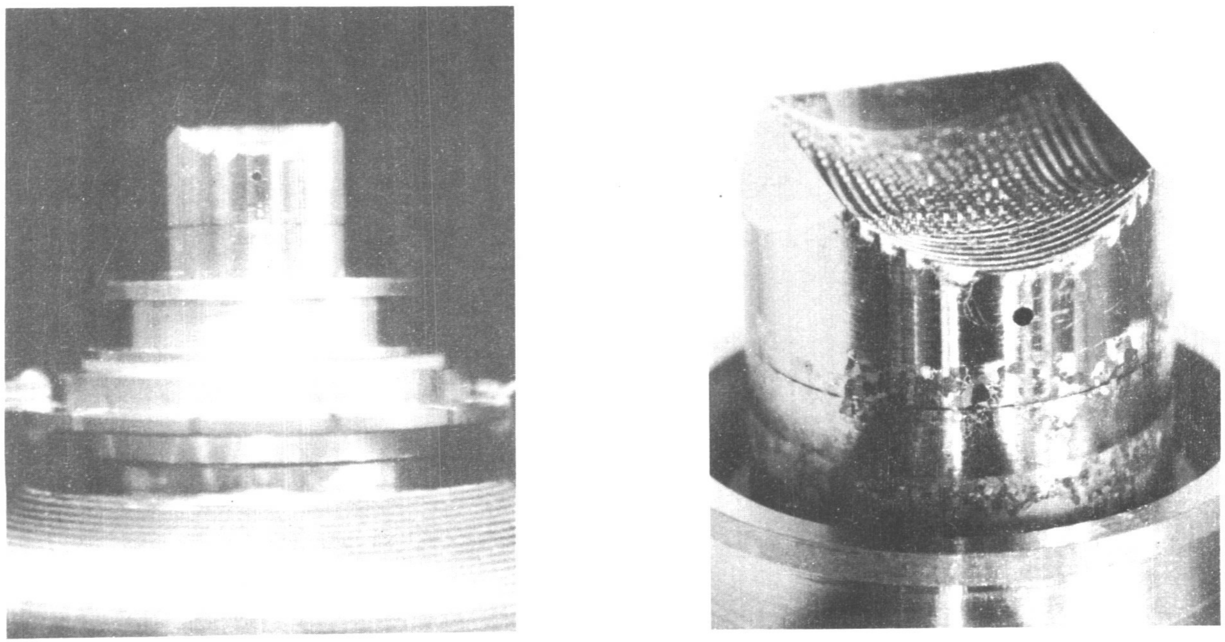

Figure 16. VI-S-18. View of Converter before and after Life Testing

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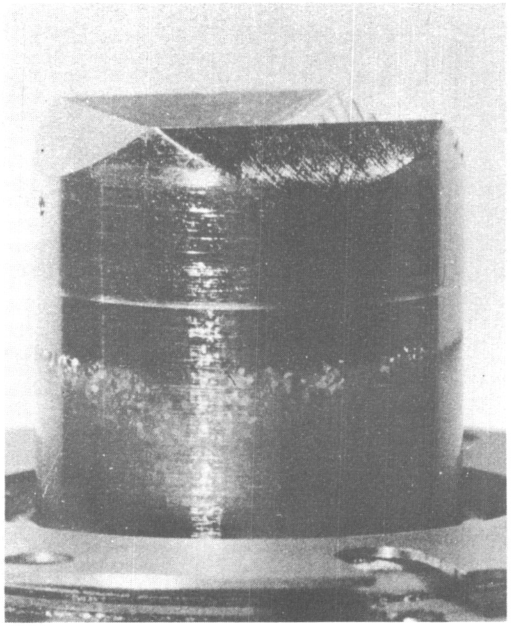

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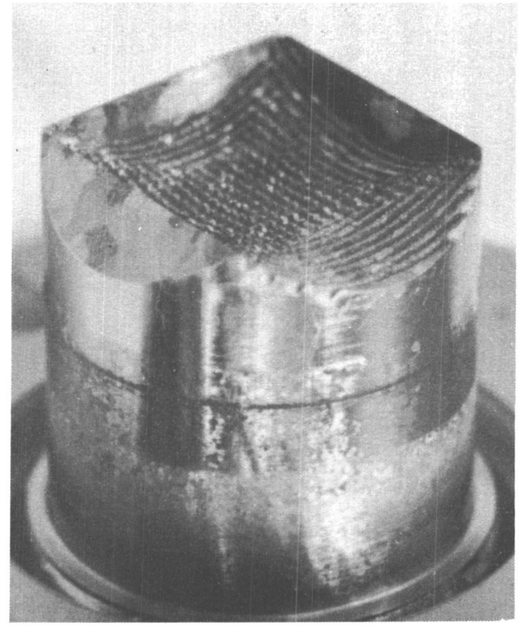

Figure 17. VII-S-4, View of Converter before and after Life Testing

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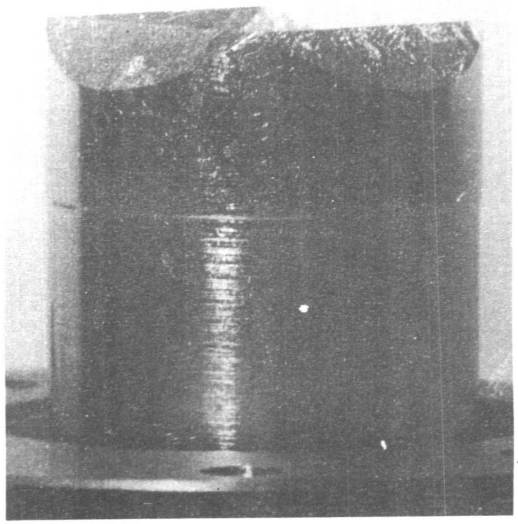

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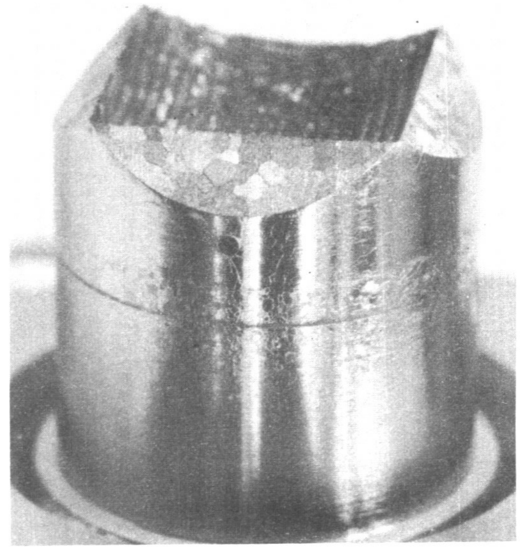

Figure 18. VII-S-5, View of Converter before and after Life Testing

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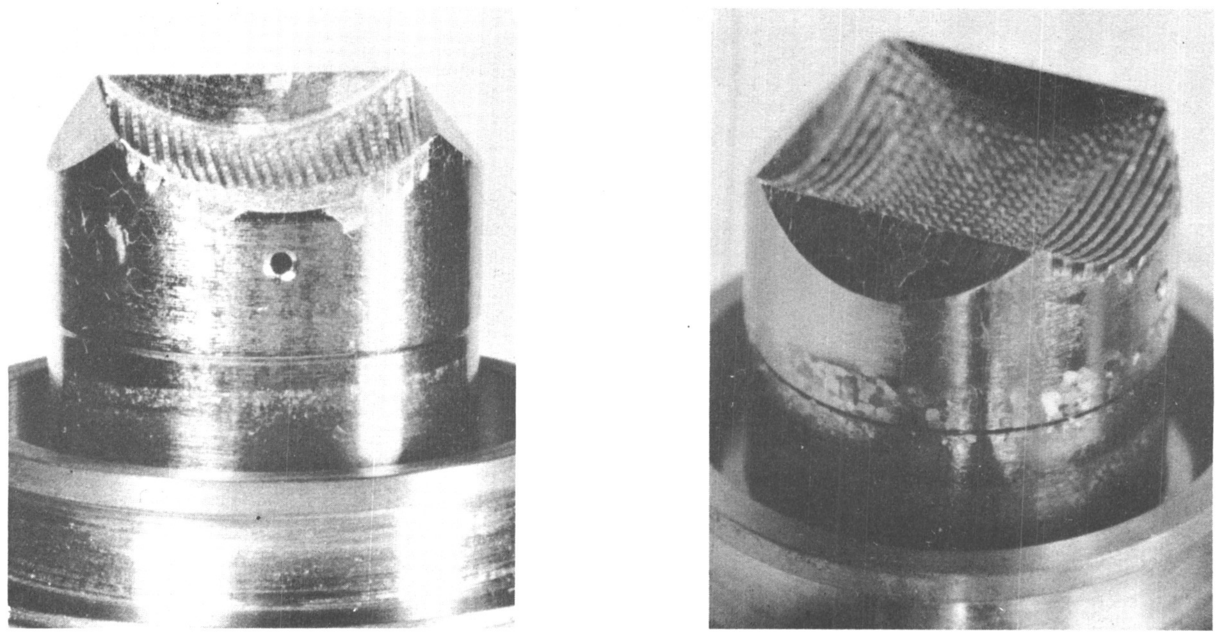

Figure 19. VI-S-14, View of Converter before and after Life Testing

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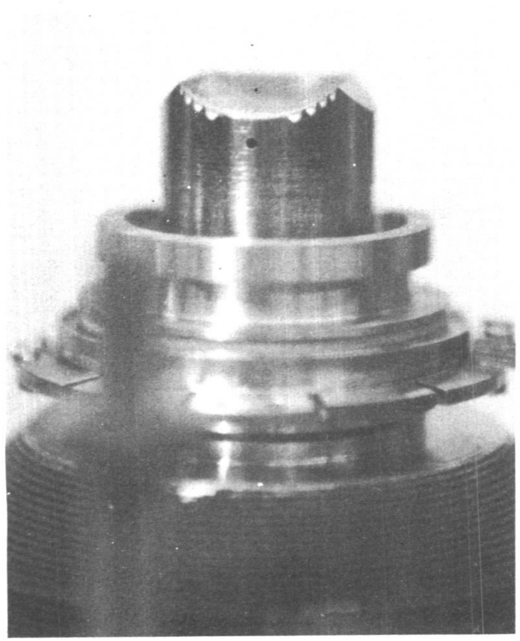

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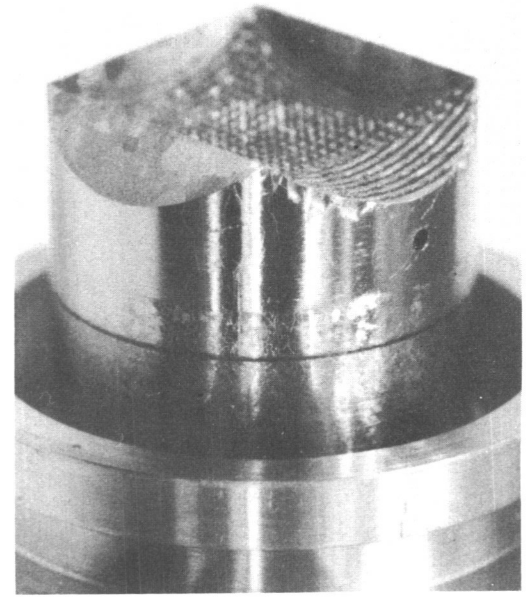

Figure 20. VI-TEP-1, View of Converter before and after Life Testing

TABLE 1

SUMMARY OF DIODE ACCEPTANCE TEST RESULTS

			VII-S -6	VII-S -7	VII-S -8	VII-S -9	VII-S -10	VII-S -11	VII-S -12
1	Amperage at 1 volt 1700° C		14.4	13.0	15.5	12.0	12.0	17.3	17.4
2	Tcs	° C	395	393	398	372	367	384	380
3	Trad	° C	583	569	581	575	600	589	584
4	Tseal	° C	678	740	649	694	737	685	682
5	Tcol	° C	628	652	628	623	649	631	637
6	EB Power (watts) 1700° C		292	450	292	300	410	315	304

TABLE 2

SUMMARY OF DIODE ACCEPTANCE TEST RESULTS

	VII-S -4	VII-S -5	VI-S -18	VI-Tep. -1
Date of Testing	6/3/63	5/22/63	7/13/63	7/17/63
Output Voltage (volts)	0.8	0.8	1.0	1.0
Output Current (amps)	19.1	18.0	13.5	8.5
Output Power Density (w/cm^2)	7.64	7.2	6.75	4.25
Power Input (watts)	335	365	328	310
Cesium Temperature (°C)	368	345	374	367
Radiator Temperature (°C)	551	540	572	564
Collector Temperature (°C)	590	583		
Seal Temperature (°C)	697	692	654	661
Observed Emitter Temperature (°C)	1655	1655	1655	1655

TABLE 3

REPORT OF INITIAL LIFE TEST RESULTS

PARAMETER	VI-S -18	VII-S -4	VII-S -5	VI-S -14	VI-Tep. -1
Date of Observation (day)	7/20/63	7/24/63	7/23/63	7/30/63	8/3/63
Time of Observation (hours)	14:00	15:30	16:00	15:30	11:00
Total Running Time (hours)	00.0	00.0	00.0	00.0	00.0
Output Voltage (volts)	1.0	0.8	0.8	1.0	1.0
Output Current (amps)	13.3	19.5	18.0	14.0	8.8
Output Power Density (w/cm^2)	6.65	7.8	7.2	7.0	4.4
Power Input (watts)	370	430	350	344	300
Chamber Pressure (mm Hg)	1×10^{-6}	3×10^{-6}	2×10^{-6}	1.5×10^{-6}	5×10^{-6}
Cesium Temperature (°C)	360	357	345	355	348
Radiator Temperature (°C)	573	579	555	583	566
Collector Temperature (°C)	623		595		
Seal Temperature (°C)	670	642	659	614	634
Observed Emitter Temperature (°C)	1665	1655	1660	1655	1655